A Meteorological Model's Dependence on Radiation Update Frequency

J. L. Eastman, C. Peters-Lidard, W.-K. Tao, S. Kumar, Y. Tian, S. Lang, and X. Zeng

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POPULAR SUMMARY

Numerical weather models are used to simulate circulations in the atmosphere including clouds and precipitation by applying a set of mathematical equations over a three-dimensional grid. The grid is composed of discrete points at which the meteorological variables are defined. As computing power continues to rise these models are being used at finer grid spacing, but they must still cover a wide range of scales. Some of the physics that must be accounted for in the model cannot be explicitly resolved, and their effects, therefore, must be estimated or "parameterized". Some of these parameterizations are computationally expensive. To alleviate the problem, they are not always updated at the time resolution of the model with the assumption being that the impact will be small.

In this study, a coupled land-atmosphere model is used to assess the impact of less frequent updates of the computationally expensive radiation physics for a case on June 6, 2002, that occurred during a field experiment over the central plains known as International H2O Project (IHOP). The model was tested using both the original conditions, which were dry, and with modified conditions wherein moisture was added to the lower part of the atmosphere to produce clouds and precipitation (i.e., a wet case). For each of the conditions (i.e., dry and wet), four set of experiments were conducted wherein the model was run for a period of 24 hours and the radiation fields (including both incoming solar and outgoing longwave) were updated every 1, 3, 10, and 100 time steps. One time step was equivalent to 6 seconds. Statistical tests indicated that average quantities of surface variables for both the dry and wet cases were the same for the various update frequencies. However, spatially the results could be quite different especially in the wet case after it began to rain. The near-surface wind field was found to be different most of the time even for the dry case. In the wet case, rain intensities and average vertical profiles of heating associated with cloudy areas were found to differ for the various radiation update frequencies. The latter implies that the mean state of the model could be different as a result of not updating the radiation fields every time step and has important implications for longer term climate studies

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Joseph L Eastman

1. University of Maryland Baltimore County, Goddard Earth Sciences and Technology Center, Baltimore, Maryland, USA
2. Code 614.3, NASA Goddard Space Flight Center, Greenbelt, Maryland, USA

Christa Peters-Lidard

Hydrological Sciences Branch NASA-GSFC Code 614.3, NASA Goddard Space Flight Center, Greenbelt, Maryland, USA

Wei-Kuo Tao

Laboratory for Atmospheres, NASA Goddard Space Flight Center, Greenbelt, Maryland, USA

Sujay Kumar

1. University of Maryland Baltimore County, Goddard Earth Sciences and Technology Center, Baltimore, Maryland
2. Code 614.3, NASA Goddard Space Flight Center, Greenbelt, Maryland, USA

Yudong Tian

1. University of Maryland Baltimore County, Goddard Earth Sciences and Technology Center, Baltimore, Maryland, USA
2. Code 614.3, NASA Goddard Space Flight Center, Greenbelt, Maryland, USA

Stephen E. Lang

1. Laboratory for Atmospheres, NASA Goddard Space Flight Center, Greenbelt, Maryland, USA

2. Science Systems and Applications, Inc. Lanham, Maryland, USA

Xiping Zeng

Laboratory for Atmospheres, NASA Goddard Space Flight Center, Greenbelt, Maryland, USA

Abstract

As the ability of high performance computing continues to rise, a trend towards finer global and regional scale numerical modeling resolutions is emerging. These models all employ a set of sophisticated parameterizations used to represent physical processes such as precipitation and radiation interactions within the atmosphere. In this study, a high-resolution modeling system is employed to investigate these interactions and the effects of calling the computationally expensive radiation parameterization at different frequencies. The results show significant divergence in the model solutions as updates to the radiation parameterization are performed at each, every 3rd, every 10th, and every 100th model timestep. The integrations were performed for cases with and with moist processes playing a significant role. In the case where moist processes dominate, there is model a significant impact on the resulting mean state of the atmosphere, suggesting that the model's "climate" could be largely affected.

Introduction

The use of parameterizations to represent physical processes in numerical models is becoming more expensive as their level of sophistication increases. These parameterizations are used to represent precipitation processes, deep cumulus convection, land-surface interactions, and long- and shortwave radiation interactions to name a few. Of these, the radiation parameterizations are clearly the most computationally expensive. For example, Majewski et al. (2002) reported that the computational cost of parameterizations occupies 46.8% of the total CPU time when the radiation code was

updated every 2 hours for high-resolution global operational numerical weather prediction models. If the radiation code (which represents 57.5% of the total parameterization cost) were to be updated on a more realistic time scale, (e.g., 10 min), this parameterization by itself would cost about 85% of the total computational time.

The frequency of radiation updates for use in mesoscale models, such as WRF, is generally performed on the order of several minutes, even when grid spacings are reduced to the order of 1km. The assumption is that the results will not be significantly affected over the course of the simulation, thus saving computing costs. In the integrations presented in this paper, the radiation more than doubles the amount of CPU time for that timestep. Tao et al. (1996) suggest that there are three of the ways in which longwave radiation is thought to interact with clouds; cloud-top cooling and cloud-base warming may alter the thermal stratification of cloud layers, differential cooling between clear and cloudy regions might enhance convergence into a cloud system, and large-scale cooling could change the environment. They also found in their simulations that the inclusion of shortwave radiation decreased the amount of precipitation by 7%.

Lee et al. (2001) employed a global circulation model (GCM) to investigate the effects of cloud-radiation interaction on the simulation of the tropical intraseasonal oscillation (ISO) by varying the characteristic parameterized precipitation timescale, which determines the life of the cloud. They concluded that this timescale has a significant impact on the simulation of the ISO through cloud-radiation interaction. Similarly, one would expect that the frequency of radiation updates and their subsequent

interaction with different types of clouds to become important at smaller timescales as one approaches the scale of a large eddy simulation (LES) where the clouds are explicitly resolved.

A rather robust study was undertaken by Pauluis and Emanuel (2003) who demonstrated that a numerical instability was linked to the infrequent update of radiation using a linear model, a one dimensional column model, and an idealized GCM. The paper also pointed out that this instability had a strong impact on the mean state of the atmosphere and that these instabilities only disappeared when the radiation was updated every timestep. Their work strengthened the results of Xu and Randall (1995) who employed a cloud-resolving cumulus ensemble model and found increasing time intervals between calls to radiation led to distortion of the cloud vertical velocities and domain averaged precipitation.

Through a series of integrations employing a mesoscale numerical weather model containing sophisticated radiation and microphysical parameterizations, these interactions and their dependence on radiation update frequency will be examined. In conjunction with this analysis, the role of update frequency for a case where no clouds form will also be examined since errors resulting from cloud/radiation modeling are typically much larger than errors resulting from the modeling of clear-sky conditions.

Experimental Design

In this study the Weather Research and Forecast (WRF) model was coupled to a land surface model (LSM) embedded in the Land Information System (LIS, Kumar et al., 2004), (here after called LISWRF). A series of integrations were performed for two different meteorological soundings in order to ascertain the effects of radiation update frequency in dry and wet regimes. The only difference between the sondes was the addition of moisture in the lowest 3km of the sonde in the WET case.

The sonde was extracted from the data archive for the International H_2O Project (IHOP) for June 6, 2002 at 12GMT. This day was chosen because there were light winds in the planetary boundary layer (PBL) and the atmosphere was extremely dry, leading to negligible moist development. These conditions are generally conducive to the growth of mesoscale circulations that can result from the differential heating of land surface discontinuities.

The modeling domain was centered near the Texas-Oklahoma border near the location of the sounding location. The domain consisted of 100x100 horizontal grid points with 1 km grid spacing and also had 41 vertical levels beginning with a 10 m spacing at the lowest level stretched to 1km spacing near the top. The soil was initialized homogeneously to the dominant soil type of the area, sandy clay loam. The soil moisture profiles were also homogeneously initialized to moderate values in between stress and saturation. Finally, the topography was set to the sonde's initial elevation of 235m, while the vegetation was initialized using the United States Geological Survey's 24-class land classification scheme, which contained information at roughly 1 km horizontal resolution.

The meteorological fields were also homogeneously initialized at all vertical levels using the information extracted from the sounding. The main modeling options

employed included the RRTM longwave (Mlawer et al.,1997)scheme, the Goddard shortwave (Chou and Suarez,1994) scheme, and the Purdue-Lin (Lin et al. (1983) and Rutledge and Hobbs, 1984) microphysics. The radiation package accounts for the effects of hydrometeors. The model timestep was set to 6 seconds for all integrations. A series of 4 integrations were performed for the dry and wet cases with the only difference being the time between calls to update the long- and shortwave radiation. This was done every timestep (hereafter the control), every third, every tenth, and every hundredth timestep.

Results and Discussion

The results were first analyzed in terms of temporal domain averages by examining a series of relevant surface related quantities. After computing these quantities, a statistical Student's T-test was performed to see if the means of the distribution were significantly different for both the dry and wet cases. In both the wet and dry cases and for all variables analyzed, the test indicated no significant differences at the 95% confidence level.

These results suggest the 100 timestep update frequency may be adequate. However, when one examines the 24-hour accumulated rainfall distribution spatially for the wet case, it becomes evident that the same is not true in a spatial sense. Shown in Figure 1 are side by side comparisons of the control rainfall distribution next to the 3, 10, and 100 timestep frequencies. The results show significant differences. The 3rd timestep patterns are the closest to the control, but diverging solutions are evident. The 100 timestep results are vastly different.

Based on the domain average the results are essentially equal. This is not surprising since roughly the same amount of energy and water goes into all of the simulations. Spatially it appears the there is a large sensitivity, at least when moist processes are in play. This is intuitive in the sense that a typical non-precipitating cloud lifetime is on the order of 10 minutes and one can visually examine an advecting cloud change on the scale of seconds. This might lead to the conclusion that infrequent updates may be adequate in the dry case.

To examine this, the Kolmogorov-Smirnov (KS) test was implemented, which can ascertain whether 2 distributions are different and to what significance level. As in the case of the T-test a probability value of 1.0 would indicate they are identical, while a value of 0.0 would imply significantly different distributions. This test was applied to the domain every 30 minutes, thus creating a temporal series.

The test included the following surface variables: heat fluxes, temperature, net long- and shortwave radiation. If a solution is nearly identical to the every timestep simulation the test probability would be near one. In the wet case, there is a period when solar heating is strong, and the every 3rd case shows statistically similar distributions for hours 1500 through 2200GMT for the variables listed above. In the every 10 case, there is a period from 1730 through 1830GMT where this occurs. Finally, the every 100 case only shows one time where the test implies the same distribution, at 1800GMT. However, as precipitation begins to dominate after 12 hours, all test results drop to nearly zero. The collapse of the boundary layer also plays a role in this drop.

The dry case shows similar behavior although the temporal length of the agreement is longer for the every 3 case and and there is some convergence in the solutions at night. In addition, the other simulations display a peak near noon. The boundary layer influence near the collapse is also evident. The results indicate that the dry case does have greater similarity in solutions for every 3, every 10, and every 100 simulations than for the wet case counterparts and is likely due to the non-linearity introduced by moist processes.

Having focused on heat-related quantities to this point, it is important to determine whether there is any effect on the momentum fields. Consequently, the horizontal winds at 10m were investigated. To do this properly, a 2D version of the KS test must be applied, since U and V are paired quantities. One would expect a continuation in the pattern. In the wet simulations, this is somewhat true although as the boundary layer develops and transient eddies become stronger agreement is limited, roughly hours 2 hours in mid morning for the every 3 case. The other two integrations have only one point in the mid morning where the distributions are the same. Since the surface winds are heavily dependent on the transfer of turbulent heat fluxes, and are highly non-linear, it is likely that the development of strong eddies in the PBL causes the divergence in the momentum fields. Again the onset of precipitation causes the solutions to become significantly different.

In the dry case, the results of the KS test on the near surface wind show the distributions are significantly different for all cases and all times except two early morning times for the every 3 integration. However, in the dry integrations there are no clouds formed, thus there is no solar attenuation by different water phases. Indeed, the boundary layer is considerably drier, and the heating goes into stronger forcing of turbulent fluxes and generates a deeper boundary layer with the related eddies. The domain averaged boundary layer height for the dry case was found to be about 200m deeper the wet runs. However, in the moist case, as clouds grow, the boundary layer height is skewed to higher values. In the case of a cumulonimbus cloud, the PBL would be about 15 km.

The wet cases are now examined in further detail by looking at the rainfall probability distribution functions and vertical heating profiles. Figure 2 displays the rain rates from the integrations by percentage of occurance, with each bin indicating a 0.5 cm/hr increment in rate. The every 3 and every 10 runs show higher probabilities at lower rain rates (< 1 cm/hr), while the every 100 tends to show higher percentages at moderate rates of 1-4cm/hr. At the far end of the spectrum, the simulations a with a radiation update every timestep and every 3rd timestep are the only ones that generate high precipitation rates. The precipitation rates are related to the vertical distribution of clouds and their subsequent heating rates.

To examine this, we created domain- and temporally-averaged profiles of heating rates were composited based on whether there was precipitation occurring. Figure 3

displays heating profiles for non-precipitating cells for all cases, the profiles are strongly correlated with correlation coefficients greater than 0.99. However, a paired T-test indicates the means are statistically different at the 99% confidence interval.

Figure 4 shows the domain-averaged heating rates for precipitating cells for all cases over the entire integration. The effects of evaporative cooling due to the precipitation are quite apparent. Since the profiles are weighted averages over each bin, the light precipitation (<1cm/hr) accounts for over 90% of the precipitation occurrences and reflected in the profile. This figure shows stronger divergence in the solutions as the update frequency increases and as the height increases. The profile for every timestep shows a warming, likely due to cirrus cloud interactions, which the other profiles do not capture. As mentioned earlier, it was pointed out in Pauluis and Emanuel (2003) that the effects of radiation update frequency produced a divergence in the mean state of the atmosphere that is clearly evident in the cirrus cloud layers. A thicker layer of cirrus clouds would tend to trap the outgoing longwave radiation and result in a net warming.

Summary

A series of high-resolution coupled land-atmosphere model integrations were performed using different radiation update frequencies. The results show that the frequency at which radiative fields are updated within a model can impact the solutions when moist processes are not prevalent. An even greater response was found at the surface when moist processes played a dominant role in the integrations, and the differences are not confined to the surface. The temporal and spatial responses of the model differed

significantly as the different update frequencies interacted with the simulated microphysics. Although the integrations were only 24 hours in duration, the cumulative effects of the interaction of radiation and clouds could resulted in a large divergence in the mean state of the atmosphere. Over the coarse of long term integrations, seasonal to decadal, this could result in different model climates due to the radiation update frequency interacting with moist processes.

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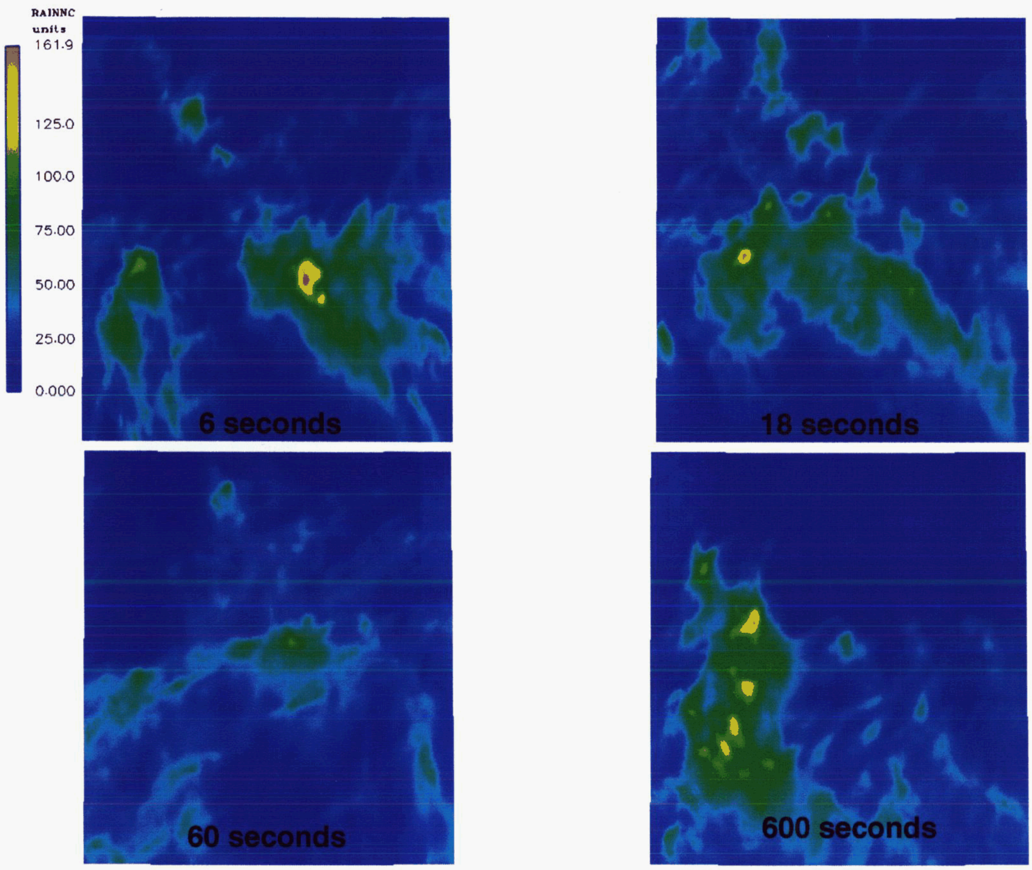

Figure 1: Total accumulated 24-hour precipitation (mm) for update frequencies at every (6 seconds), every 3 (18 seconds), every 10 (60 seconds), and every 100 (600 seconds) timesteps.

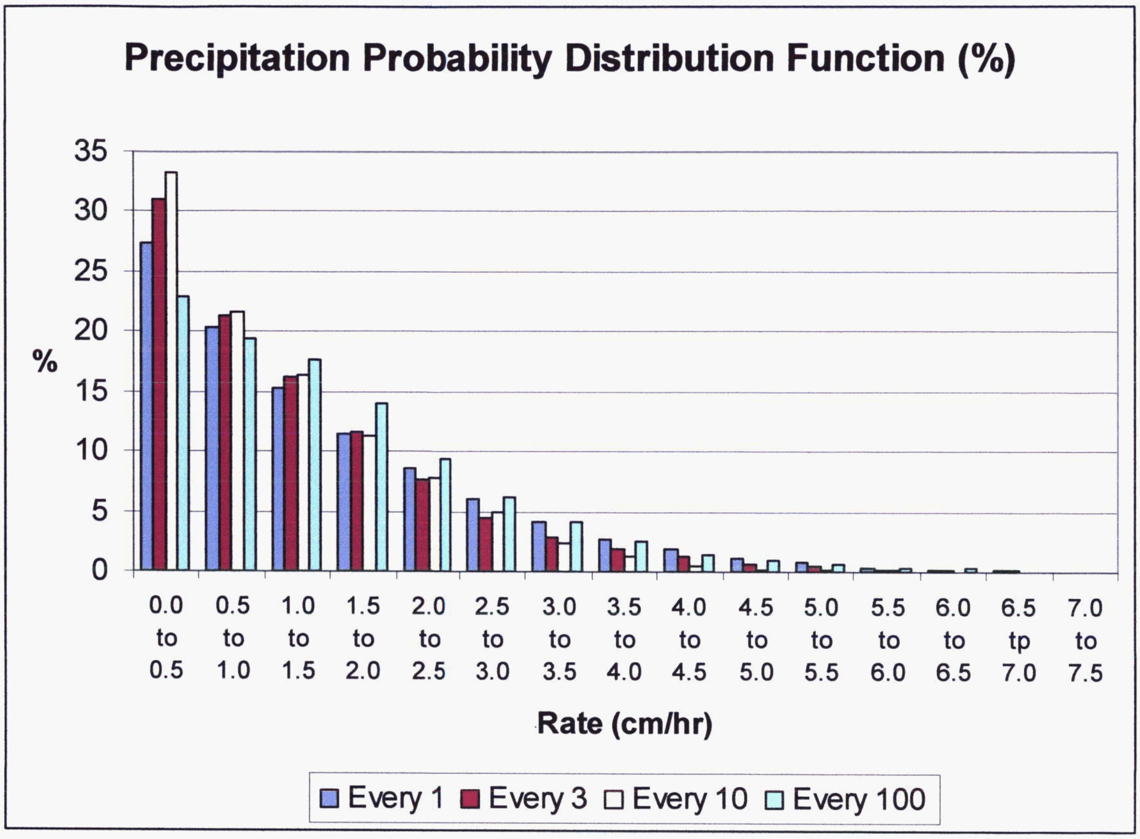

Figure 2 : Probability distribution function for radiation update frequency for every (blue), every 3rd (red), every 10th (yellow), and every 100th (green) timestep binned in 0.5cm/hr increments.

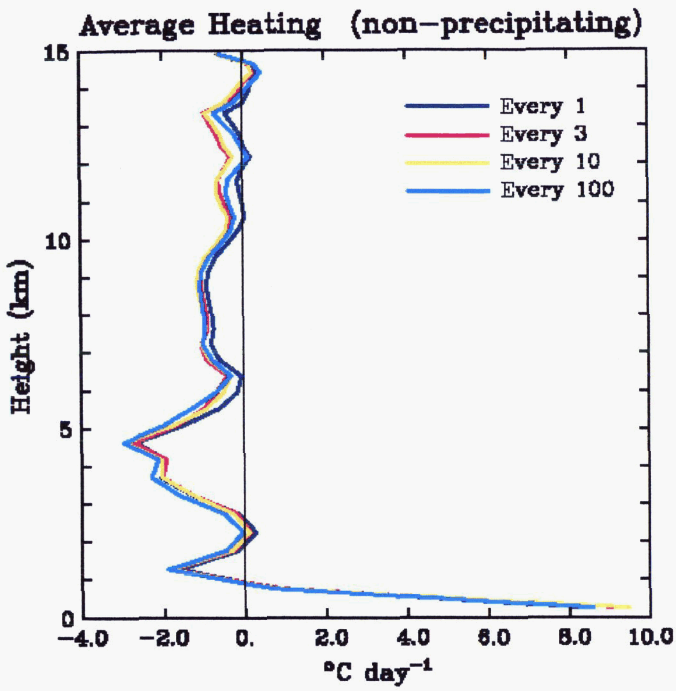

Figure 3: Domain and temporally averaged vertical heating profile (C/day) when no precipitation is occurring for every (blue), every 3 (pink), every 10 (yellow), and every 100 (blue-green) timestep.

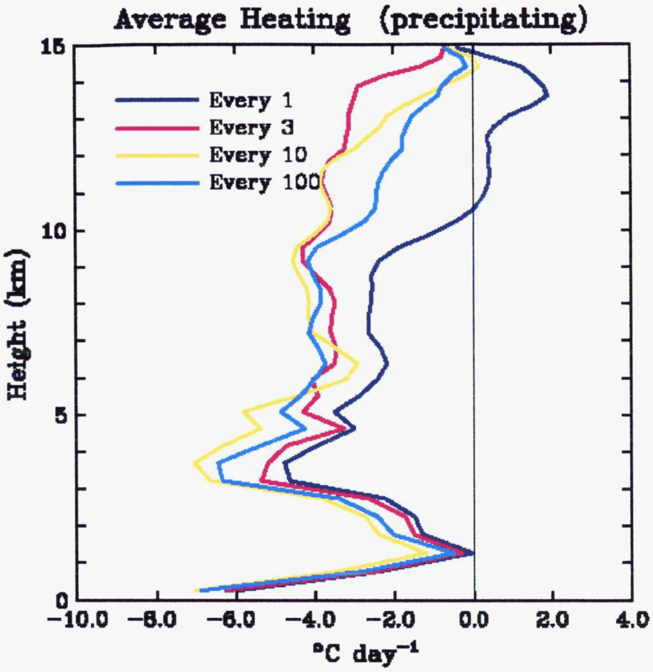

Figure 4: Domain and temporally averaged vertical heating profile (C/day) when precipitation is occurring for every (blue), every 3 (pink), every 10 (yellow), and every 100 (blue-green).

Statement of Significance

A series of high-resolution coupled land-atmosphere model integrations were performed using different radiation update frequencies. The results show that the frequency at which radiative fields are updated within a model can impact the solutions when moist processes are not prevalent. An even greater response was found at the surface when moist processes played a dominant role in the integrations, and the differences are not confined to the surface. The temporal and spatial responses of the model differed significantly as the different update frequencies interacted with the simulated microphysics. Although the integrations were only 24 hours in duration, the cumulative effects of the interaction of radiation and clouds could resulted in a large divergence in the mean state of the atmosphere. Over the coarse of long term integrations, seasonal to decadal, this could result in different model climates due to the radiation update frequency interacting with moist processes.